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# Long Baseline Correlation Experiments

[Unclassified Title]

D. C. COULTER AND H. L. PETERSON

*Electronics Branch*
*Sound Division*

July 25, 1967

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CONTENTS

## ABSTRACT
(Secret)

A preliminary experiment to measure the existence of signal coherency over very long baselines is described. Data for these measurements was obtained by NRL with the cooperation of USNUSL in allowing collaboration with their previously scheduled ARTEMIS propagation experiment. The data was recorded at SOSUS stations, mostly by NRL personnel for data processing at the Laboratory via digital computer. Initial results indicate the correlation coefficient of about 0.35 observed for one data run over a baseline distance of 450 nm. Additional field collection and laboratory analysis are planned to establish the range of possible values with greater accuracy and consistency. These studies are believed relevant to Navy needs, as follows:

1. Research evaluation of methods of on-line processing of signals brought to a central point from several SOSUS arrays.

2. Study of long range acoustic propagation to widely separated reception points.

3. Consideration of methods of target localization by triangulation from two or more widely spaced arrays.

In addition to the above, there is some indication of possible jamming effects on SOSUS stations in the upper portion of the frequency range, by pseudo-random noise signals of sequence length utilized for this experiment.

Follow-on experiments to further illuminate the above problem areas are planned.


## PROBLEM STATUS

The work described in this report is an independent part of a l r, more general problem. This work is continuing. The parent problem .. a continuing one.

## AUTHORIZATION

NRL Problem 55S01-06
Project ONR RF 101-03-44-4054

# LONG BASELINE CORRELATION EXPERIMENTS

## The Program

The Electronics Branch, Sound Division, has undertaken a program of measurement of cross-correlation of signals, transmitted over long underwater paths and received at widely spaced stations (in the order of hundreds of miles). These measurements are made utilizing a towed, low-frequency source, transmitting known signals, which are received and recorded at existing SOSUS Stations located in the Southwestern Atlantic Ocean. The recordings made at these stations are brought back to NRL where they are analyzed using digital crosscorrelation techniques between pairs of stations.

## Relevance to Navy Needs:

There are several areas of application to passive underwater surveillance system improvement to which results of this program appear relevant. These are:

1. Research on methods of exploiting the availability of the outputs of several SOSUS arrays at one centralized station.

2. Study of propagation effects on widely spaced receiver locations, as related to received signal coherency*; variability of reception as the target ship moves through separate convergence zones associated with widely spaced receivers, and other factors relating to long range signal propagation.

3. Consideration of methods of target localization by means of cross fixing, where cross-correlation is employed to verify a common target between two arrays.

In addition, results of the preliminary experiment to be described may be relevant to possible methods of jamming the SOSUS network, although this was not entirely anticipated in the initial planning of the program.

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* Lack of coherency, for the purposes of this report, refers to lack of identicalness of signals received at widely separated points from a common acoustic source.

All of these areas are of importance to the future improvements to the passive network, and the outcome of this study should affect this future by providing factual information on the amount of coherence which can exist over long baselines, on the conditions required for best correlation and on methods of processing the data from several stations to achieve improvements over present performance in identification and localization. Also, if a potential threat of jamming is found to exist, then it may suggest methods of countering such a threat.

In addition to the above goals, it is also intended to further explore the characteristics of certain signals, notably various types of pseudo-random noise, for possible future application to extremely long-range active sonar systems. This requires the definition of the ambiguity function of these signals under various conditions of doppler, various sequence lengths, bandwidths, and the like. This goal is not inconsistant with the passive detection objectives stated above, but represents a longer term research program within the Electronics Branch.

DESCRIPTION OF PRELIMINARY FIELD EXPERIMENT

The following is a description of a preliminary field experiment performed in September, 1966. Also described are some of the results of analysis of the data gathered during this experiment.

GENERAL

In order to generate data to be used for cross-correlation analysis, it was determined that a shipborne, low-frequency signal source in the deep ocean would be necessary, whose output could be received and recorded at a number of widely separated fixed stations, at distances of up to several hundred miles. These recordings would be brought back to the Laboratory for later cross-correlation analysis of station pairs, yielding values of correlation coefficients.

It was desired to first run a preliminary experiment to gather data quickly and to assist in planning future operations. In order to facilitate this, it was decided to attempt to collaborate the experiment with an already planned operation, thereby bypassing the delays normally incurred in planning an operation, including those normally incurred in the procuring of ship's services.

COORDINATION OF EXPERIMENT

An opportunity for a coordinated operation was afforded by a USNUSL experiment led by Don Cobb. Their operation involved the USS WITEK, a DD, and was scheduled for 24-30 September 1966. The WITEK was equipped for the USNUSL experiment with a 10 KW driver and was to tow a transducer assembly at a depth of 450' which contained 3 omnidirectional units resonant at 178, 400 and 1000 Hz. The 178 Hz unit was believed suitable for the NRL experiment, since its resonant frequency was low enough to be received on all SOSUS stations. The possibility of using these stations for reception was considered crucial because they represented the only operating system of widely spaced, bottom mounted, steerable arrays.

It was necessary to coordinate with the USNUSL transmission schedule in such a way as to not disturb their operation and still be able to realize useful results for the experiment. Their schedule consisted of virtually continuous transmission of 50-ms pulses at 5-second intervals, alternated between each of the three frequencies. Fortunately, they had planned to transmit a brief marker signal once each hour, so it was a relatively simple matter to substitute our source generator for this hourly marker.

The choice of the signal to be used was based on previous NRL experience in correlation analysis over long ranges. Although almost any signal such as a sine wave could have been used, the signal actually chosen was pseudo-random noise, which has a number of advantages for this type of study. In the first place, pseudo-random noise (PN), although filtered for acoustic transmission, has a broader band of frequencies than a sine wave, thus providing more information about the transmission versus frequency in the water medium. In addition, since the energy contained in a complete PN cycle is integrated to define the value of each correlation coefficient, it provides a description of the long baseline coherence averaged over a longer interval of time than would be the case for a sine wave.*

The choice of PN sequence length was limited by the maximum length which could be correlated at one time on the present computer system, if it were to be sampled at a reasonably ample sampling rate. For the Electronics Branch DDP24 computer, the maximum length sequence which can presently be accommodated in core memory is 1280 samples. When the received signal is sampled at 1000 samples per second (about 3 times the Nyquist rate), the computer is able to accommodate a PN sequence length of up to 1.28 seconds.

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* This is because fewer peaks result in the correlation function of PN due to the longer period of a PN sequence. A sine wave at operating frequency has a correlation function which is a cosine wave of the same period as the input sine wave. The presence of so many peaks in the result leads to ambiguity of interpretation.

In order to achieve such a sequence, a total of 10 stages of shift register were employed, resulting in a sequence length of 1023 bits. This was shifted at a rate of 800 per second, yielding the desired sequence period of exactly 1.28 seconds.

The output of the sequence generator was band limited to accommodate the transducer characteristics by means of a filter centered at 178 Hz with a bandwidth of 15 Hz. This signal was then slightly clipped * to eliminate occasional peak overloading of the driver, and transmitted continuously for 3 minutes out of each hour. This length of transmission was chosen to improve chances of securing an adequate recording. The resulting transmission system for the joint NRL-USNUSL experiment is shown in Figure 1.

Details of Operation

A brief description of the operation follows. As shown in Figure 2, the WITEK started on a course of 226$^{o}$T from Argus Island, Bermuda, and held this course until close to San Salvador, Bahamas. They proceeded at maximum towing speed which was only about 6-7 Kts, since the towing cable was faired for only about 200 ft.

Receiving stations utilized existing SOSUS locations, and were located at Bermuda, Cape Hatteras, Eleuthera (2 receivers available), San Salvador and Grand Turk. NRL personnel manned the NRL portable magnetic tape recorders at Bermuda, Eleuthera and San Salvador Stations. Navy personnel manned station recorders at the other locations.

All stations were instructed to record the signals received at least 3 times daily; at 0800, 1100 and 1600 hours, Romeo (Eastern Standard) time. Originally it was planned to record only at NRL-manned stations, but the other stations were requested by Naval Message to record also, since signal reception appeared good.

Recording of Signals

A chart showing the actual runs recorded is shown in Figure 3. It may be observed from this chart that many additional runs were recorded when signals were good, whereas occasionally desired runs were skipped because of equipment problems or insufficient signal strength.

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* The clipped signal was subsequently refiltered to reduce spurious frequencies introduced by clipping.

The signals recorded on different channels of magnetic tape at a given station consisted of the array output from the received beam indicating greatest signal strength (on the 140-280 Hz LOFAR auxiliary), the outputs of the two extreme end hydrophones of the array, a 1000 Hz frequency standard tone for use in later digital sampling and WWV time signals, where available. At two of the stations narrow band pre-filters were used to improve recorded signal-to-noise ratio.

A few difficulties were encountered in getting good recordings at all stations for all runs, due mostly to recording equipment malfunction. These difficulties did not prevent collection of considerable useful data, however, and these problems will be corrected in future runs where more time is available for proper instrumentation.

Choice of Runs and Method of Data Analysis

Two specific runs were chosen for initial processing, based on availability of good recordings from most stations for these runs. Broad-band signal-to-noise ratios of greater than 6 db were observed in most cases, and hence the signal strength was greater than that commonly observed for ship targets. Charts depicting the approximate ship positions and acoustic paths are shown in Figures 2 and 4.

The method of reading the data into the digital computer is shown in Figure 5. As shown in the Figure, the runs chosen were first encoded into digital form, being sampled in synchronism with the previously recorded 1000 Hz reference frequency tone. Sampling in this manner substantially reduced the effects of wow and flutter in the recording, since the sampling standard frequency also underwent essentially the same speed variations as the data. The sampled data was recorded on a Potter Digital Recorder. This digital recording system is also used by the Electronics Branch as a digital field data recording system.

Each selected signal, having been digitized and recorded on the digital recorder, was now transferred into the DDP24 computer and reformatted by the computer into 640 word blocks on the computer tape unit. The appropriate data from one of the chosen stations was selected to be read into the memory.

As shown in Figure 6, two blocks are selected for storage in core memory making a total of 1280 words for one input (called the "X" block), for correlation. The data for the other correlation input (called the "Y" block), (either from the same location if autocorrelation is to be performed, or one from a different location for crosscorrelation) is read into core memory in 3 block lengths, containing a total of 1920 words of data. The extra block length is provided to allow space for shifts of Tau delay during the correlation computation. As indicated in the Figure, when a Tau shift of 640 words is completed, the value of relative addressing is reset to zero, and the next block of 1920 words are shifted into core memory, by adding 640 new words and shifting the remainder so that 640 words are lost from the other end. By this method, effectively continuous Tau steps can be provided up to any length. The main limitation of the system stems from the lack of sufficient core storage available in the computer to provide a longer sample for the "X" block reference signal.

## Presentation and Discussion of Results

Some selected results are shown in Figures 7 and 8. In Figure 7 are shown typical autocorrelation results. These are obtained by correlating the signal at a single station against itself. As can be observed, they show a high degree of correlation when Tau is equal to zero or is equal to exactly one sequence length, with only a small reduction in correlation coefficient from a value of 1.00 to a value of about 0.75 for Tau values many multiples of the sequence length. This indicates that under these recorded conditions, the decrease of autocorrelation coefficient was not too great at Tau equal to values of up to several sequence lengths.

It should be noted that for each autocorrelation function shown, the first one or two peaks at the left of the chart are much lower than succeeding peaks, and are different in character. Since the data in the X block is always chosen from a point in the received signal far enough in from the beginning to insure a well established signal,* it appears that the lower peaks at the left side of the chart occur when a signal taken from a well established point of signal transmission is correlated with the first or second PN sequence received, before all multiple transmission paths have been established. This observation is somewhat strengthened by the presence of multiple peaks later on in the correlation function when all of these paths presumably are being received.

Note that in the bottom chart, made from data recorded at San Salvador, a broadening and smoothing of the peaks of the autocorrelation function can be observed. This effect is due to the fact that the recording was made after passing the received signal through a narrowband pre-recording filter, and the width of the peak is inversely related to the bandwidth of the input function.

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* They are chosen to be from 6 to 15 640-word data blocks after the first signal reception is observed. Data blocks are marked in the figure by pulses in the lower half of each chart.

In Figure 8 are shown some results of signals crosscorrelated between two stations. Of course, the crosscorrelation peaks corresponding to Tau values equal to multiples of the sequence length are much lower, in the order of about 0.35, since this data is for very long baselines and path lengths. In the top chart of the Figure, the path length from the WITEK to the receivers is approximately 360 nautical miles, and the distance between receivers or baseline distance is approximately 450 nm.

One factor of interest observable from Figure 8 is the large number of multiple correlation peaks observed for each sequence length, presumably indicative of signals being delayed by varying amounts due to multipath propagation. These peaks demonstrate the ability of the correlation process to descriminate various path delays even when continuous rather than pulsed signals are transmitted. They also indicate that a higher crosscorrelation peak could be obtained if some method of aligning these received signals were available. Not shown in the Figure are the results of other pairs of stations which were also crosscorrelated. While these results were somewhat poorer, definite indications of some coherency were observable in every case. It is believed that the deterioration for many of these runs is due to the large relative doppler shift between the stations. A future effort will be made to compensate for the difference in relative doppler between stations by resampling the data at compensating rates, which should improve the crosscorrelation coefficient obtained by a noticeable amount.

## Harmonic Structure of PN Signals and Jamming Potential

A typical Lofargram of the received PN signal is shown in Figure 9. In this Figure are shown two PN sequences which have been Lofar analyzed after having been propagated about 300 nm. They can be identified as a series of closely spaced horizontal lines (discrete frequencies) covering the entire frequency range of the Lofargram for 3 minutes and spaced one hour apart. (The single frequency line at 178 Hz present for the remainder of the time is due to pulses at this frequency emitted every 15 seconds). It should be noted that the spacing of these lines occurs at the reciprocal of the PN sequence length, i.e., 1/1.28 sec = 0.78 Hz.

Observing the ability of this signal to cover a rather wide range of frequencies with rather closely spaced striations naturally gave rise to speculation concerning possible jamming of the SOSUS network with signals of this type, propagated continuously, rather than for 3 minutes each hour. No definite assessment or probable effectiveness of such jamming can be given at this time, since the present signals are largely confined to the "Extended Spectrum" range of frequencies, and it is of course difficult at present to radiate much power at the lower frequencies

(10-150 Hz) for this type signal. However, it does seem apparent that a moderate power (approximately 100 db re 1 dyne/cm at 1 meter acoustic power level) source could cause some jamming effects in the extended spectrum region if continuously operated. In addition, it appears that if substantial low frequency energy could be generated by some method, such as rapid small explosions or high energy spark discharges, an effective means of jamming might be produced.

Use of PN Source to Observe Frequency Selectivity of Medium

An interesting observation which can be made from these Lofargrams is the varying patterns of light and dark which are observed to modify the harmonics. Since these patterns are changing during each 3 minute run and from one hour to the next, it appears that valuable new information relating to reinforcements and cancellations at various frequencies due to transmission effects, such as multipath, might be obtained by making a long continuous run of the PN signal, and then analyzing it utilizing standard LOFAR equipments. Further studies of this phenomenon are planned as a portion of future operations.

Plans for Future Operations

Results of these preliminary studies are deemed of sufficient interest to justify an additional field experiment to gather better data and allow for a number of additional measurements. Such a trip is planned for August, 1967. The proposed course of the target is shown in Figure 10. One purpose of the trip is the gathering of additional data for baselines of 60 to 600 nm. Figure 10 also shows a number of loop maneuvers for the purpose of gathering additional data with variable doppler shift at the various stations. This data will be used for 2-dimensional correlation analysis which can be further processed to produce the ambiguity surface. It is hoped to achieve much better performance of field recording systems by utilizing the available lead-time for planning and execution of more adequate instrumentation. In addition, a provision for monitoring the relative level of signals at each station will be provided, and the possibility of some degree of absolute level calibration at each station is being investigated.

Although planning is not finalized, certain additions are being considered in the acoustic transmissions to be used. For example, the effect of varying the PN sequence length to ascertain the effects of various types of sequences is being considered along with a short pulse transmission as a means of studying each multipath situation. At least one experiment is planned for a continuous transmission of PN data for a relatively long period, say for an hour or more, to gain insight into this method of observing ocean frequency transmission variations over a relatively long period of time, and to further observe the amount of "covering up" or smearing which this signal produces on other line spectra such as produced by targets.

Additional refinements in laboratory analysis are also in the planning stage, including doppler compensation of the station pairs, by interpolation and resampling of the field data. Techniques for target localization by means of correlation analysis are also being considered.

Contacts have been made with ONR, BTL, and STIC-III for comments and possible interest and help in recording relative sound propagation levels at each of the receiving stations.

In addition, ideas or suggestions from these or other sources will be welcomed and utilized if they can be reasonably integrated with the operation.

## CONCLUSIONS

Based on the preliminary results presented in this report, conclusions must be tentative in nature. These are as follows:

1. Significant signal coherence does indeed exist over paths of 300 nm or more, and baselines of at least 450 nm. Correlation coefficients of approximately 0.35 have been obtained (for received broadband S/N ratios of at least plus 6 db) and higher values are likely with refined data collection techniques and relative doppler compensation.

2. Use of short PN sequences such as 1.28 seconds used in this experiment promises to be useful in defining water transmission characteristics, multipath conditions, and variations of the medium with time and other factors. It may also be a useful type of signal to study with regard to possible jamming of the SOSUS network at least in the upper frequency range.

3. A possible area for future exploration lies in the use of the signal coherence over long baselines as an aid to improved target localization. If crosscorrelation of target noise can be observed, this can provide increased certainty that the same target is under observation by two widely separated SOSUS stations. Although the high repetition rate of most mechanical sources provides little assistance in resolving ambiguity of exact position within an area of intersection between beams of two stations, it is possible that transient target sounds may provide such a clue, allowing for exact cross fixes by means of triangulation. Such techniques will only become possible as the outputs of many stations are made available at one central processing point, however, laboratory evaluation of their potential can be performed by means of field experiments like the ones described in this report.

## SUMMARY

The Electronics Branch, Sound Division, NRL, has conducted a preliminary research experiment as part of its program in the determination of signal coherency over long baselines. This experiment utilized a signal transmitted by a surface vessel utilizing a towed array transducer and received at several SOSUS stations in the Atlantic Ocean. It was established by crosscorrelation measurements between signals that some signal coherence does exist (crosscorrelation values of about 0.35 were observed for a baseline of 450 nm) but additional field experiments are needed and planned to determine the exact amount with useful accuracy.

It is believed that the results of this and planned successor experiments are relevant to Navy requirements for continued improvement in passive underwater surveillance in the following areas:

1. Research evaluation of methods of on-line processing of signals from several SOSUS arrays, when and if these signals become available at a central location.

2. Study of simultaneous long range acoustic propagation received at widely separated points, as related to multipath and other time and range varying characteristics.

3. Providing information, useful in efforts to aid target localization by triangulation of two or more widely spaced arrays.

In addition to the above areas, it appears that the particular signals used in the preliminary experiment described in the body of the report (repeating pseudo-random noise sequences of 1.28 second duration) may possess capability of jamming the SOSUS network in the frequency regions in which they can be radiated with sufficient power, based on observations of LOFARGRAMS taken during the experiment. Further study would be needed to determine whether such jamming potential exists, what power levels would be needed, whether such power levels are feasible at lower frequencies, and so forth. Experiments are presently planned at the same frequency range and sequence length used previously, which should provide additional information.

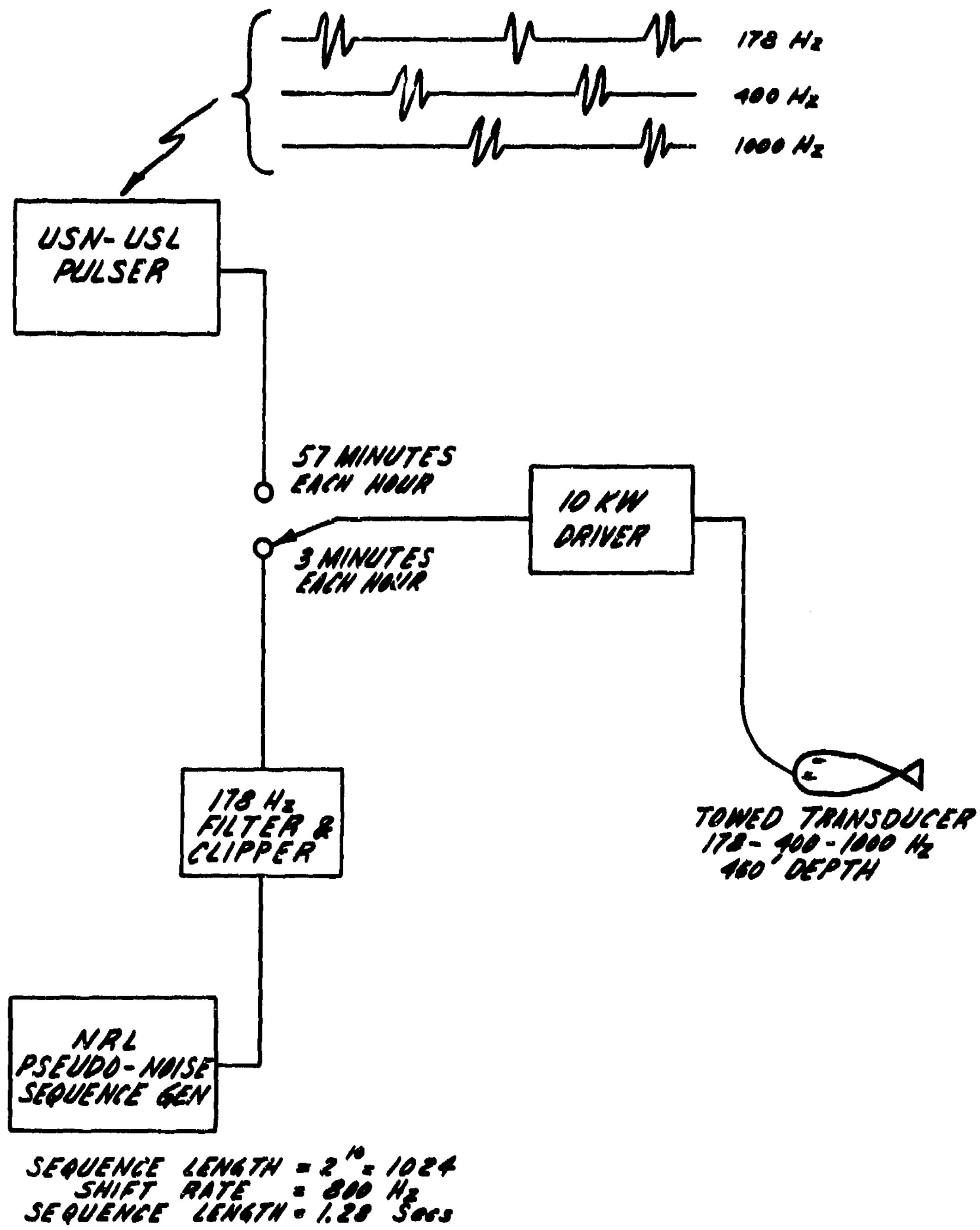


Fig. 1 - Block Diagram, acoustic transmission setup, NRL-USNUSL combined experiment

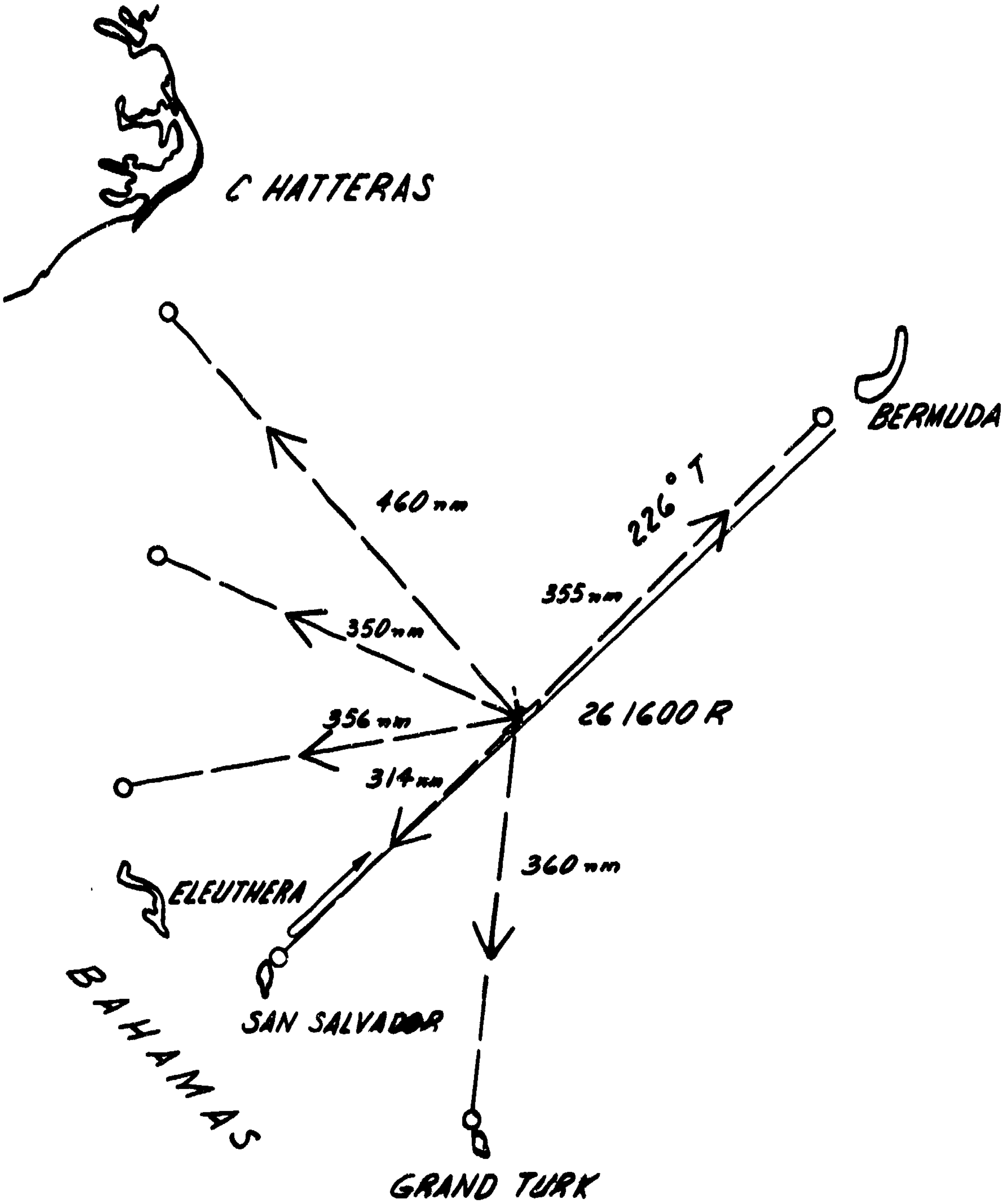


Fig. 2 - Plan of ship operation showing acoustical paths on Sept. 26 at 1600R

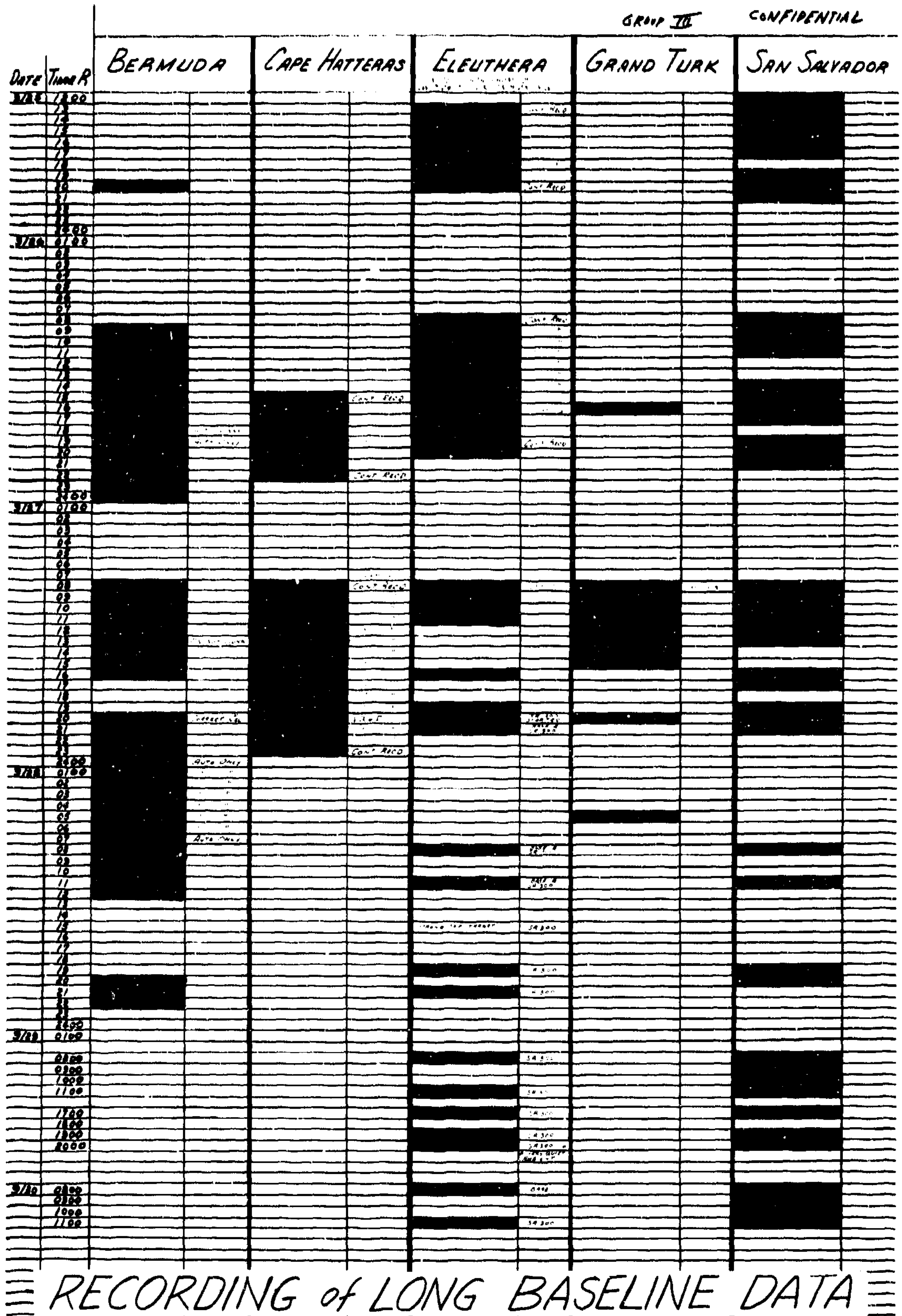


Fig. 3 - Chart showing times of recordings made at each listening station

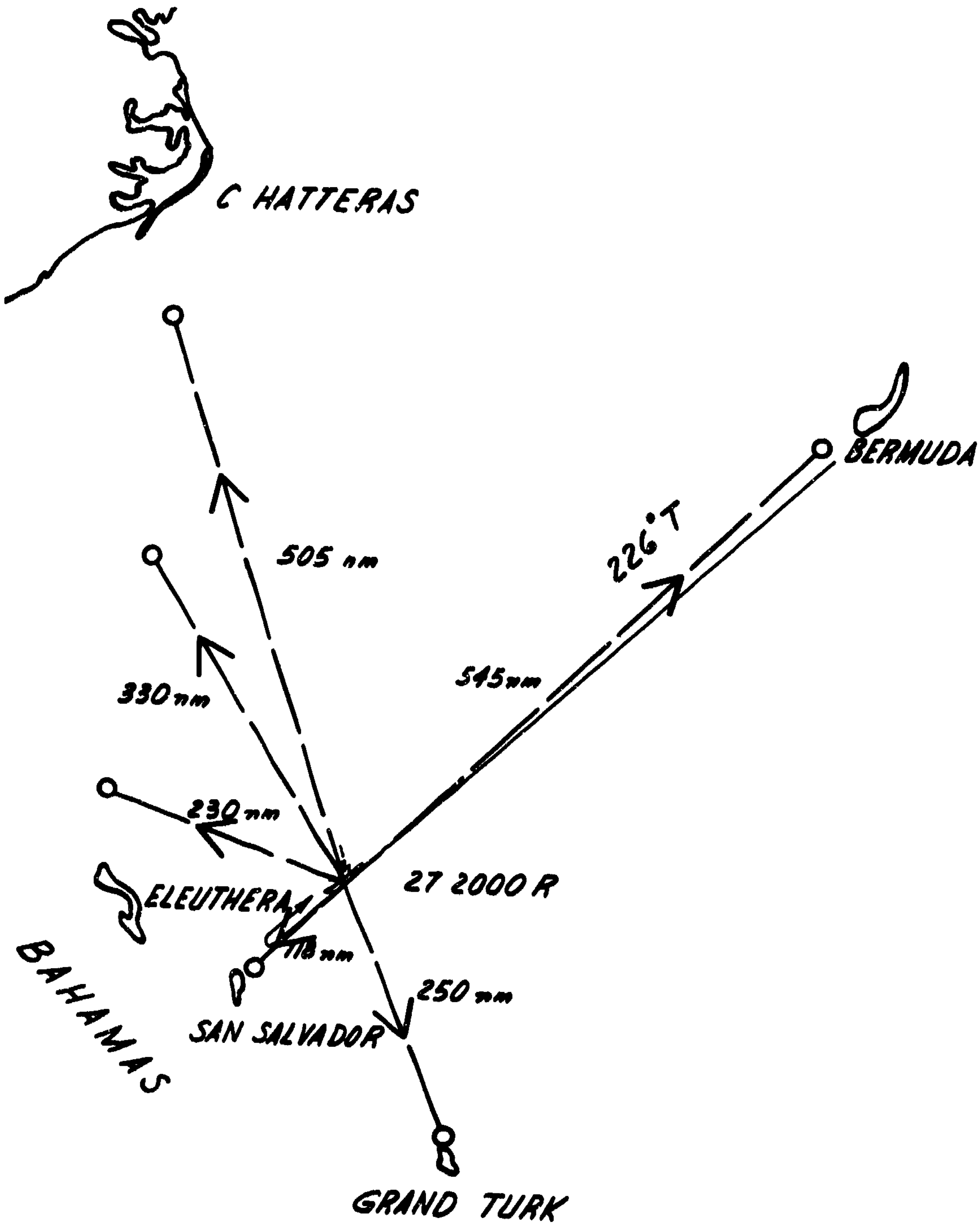


Fig. 4 - Plan of ship operation showing acoustical paths on Sept. 27 at 2000R

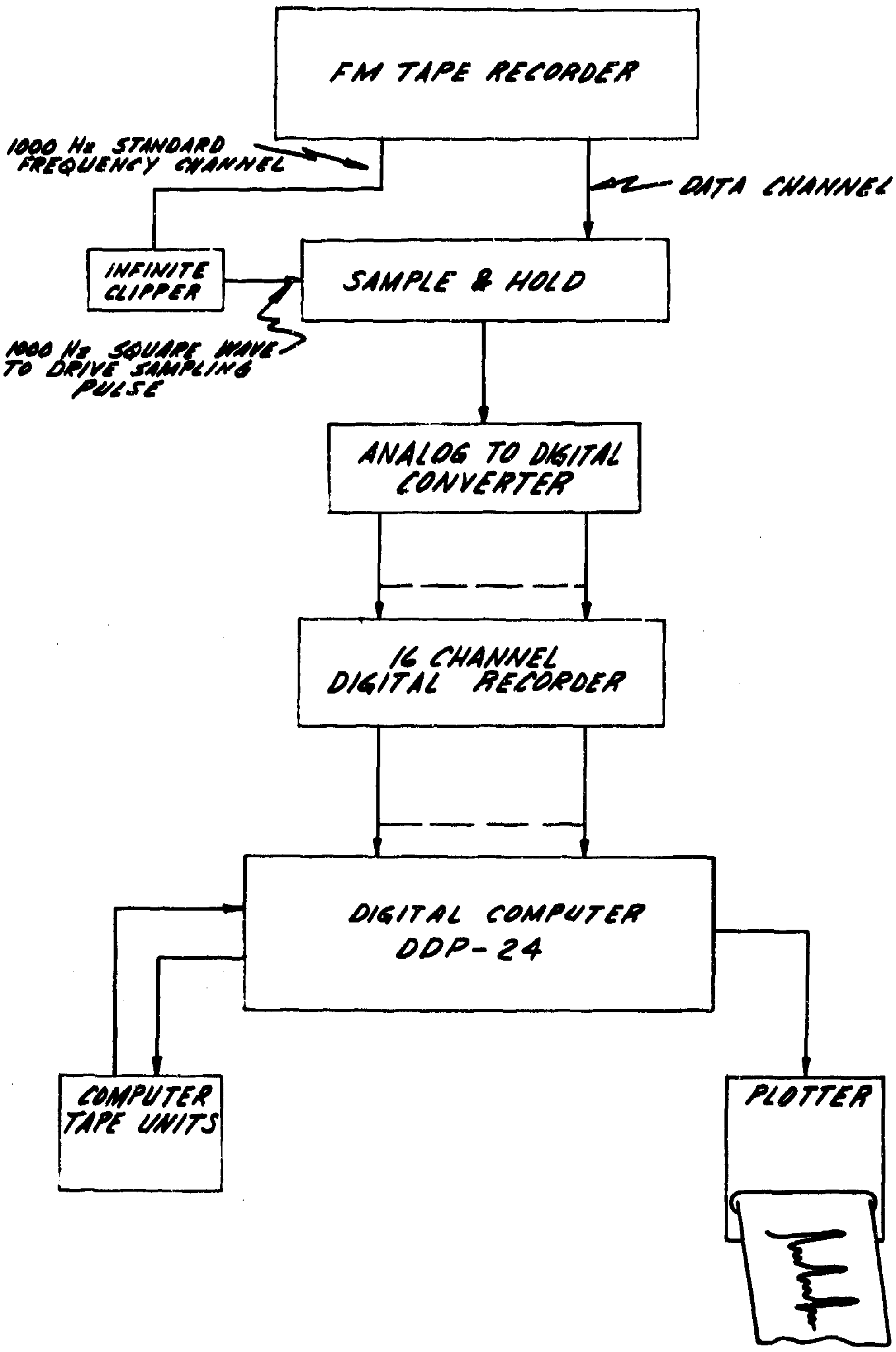


Fig. 5 - Laboratory digital data conversion and processing arrangement

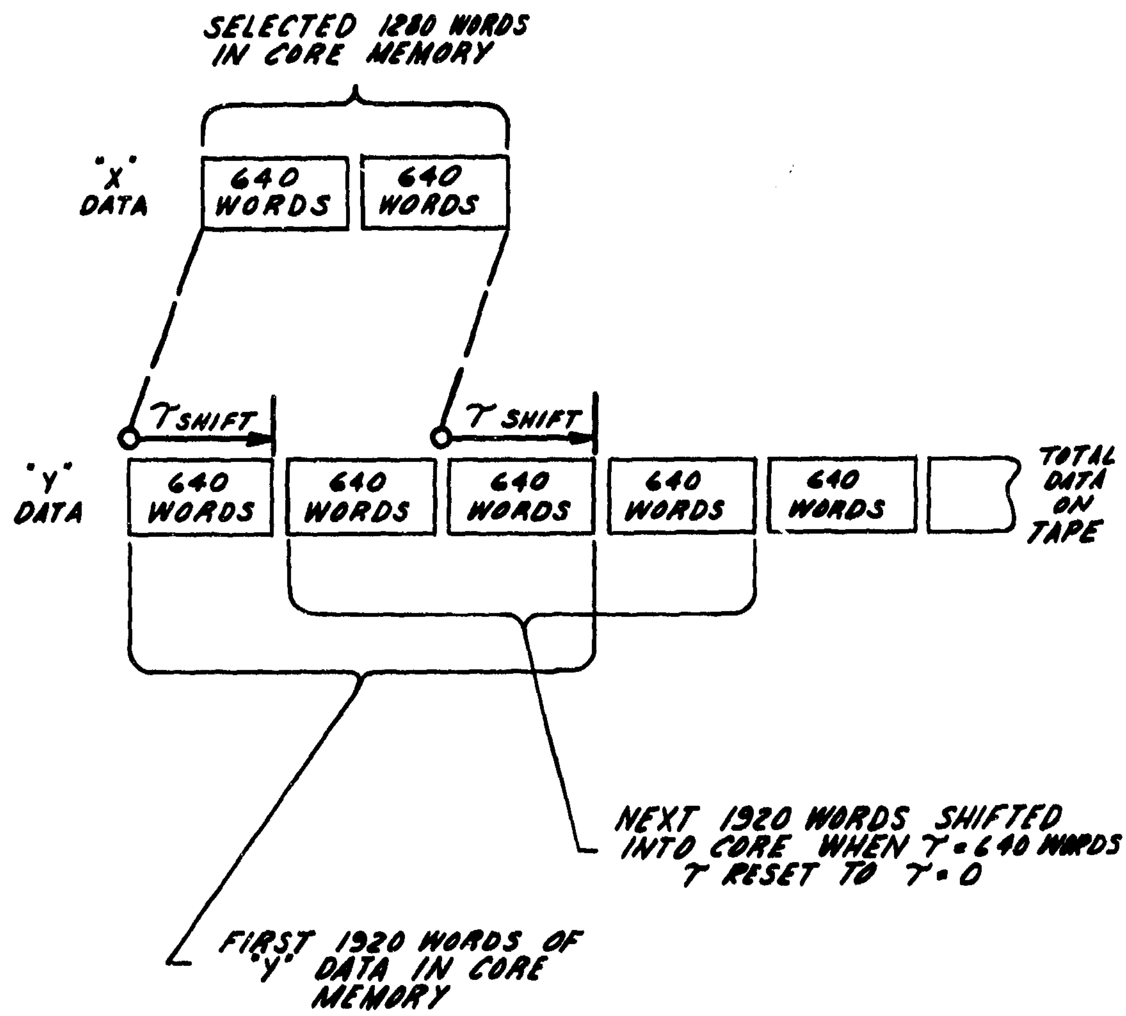


Fig. 6 - Diagram showing data storage for computation of correlation function

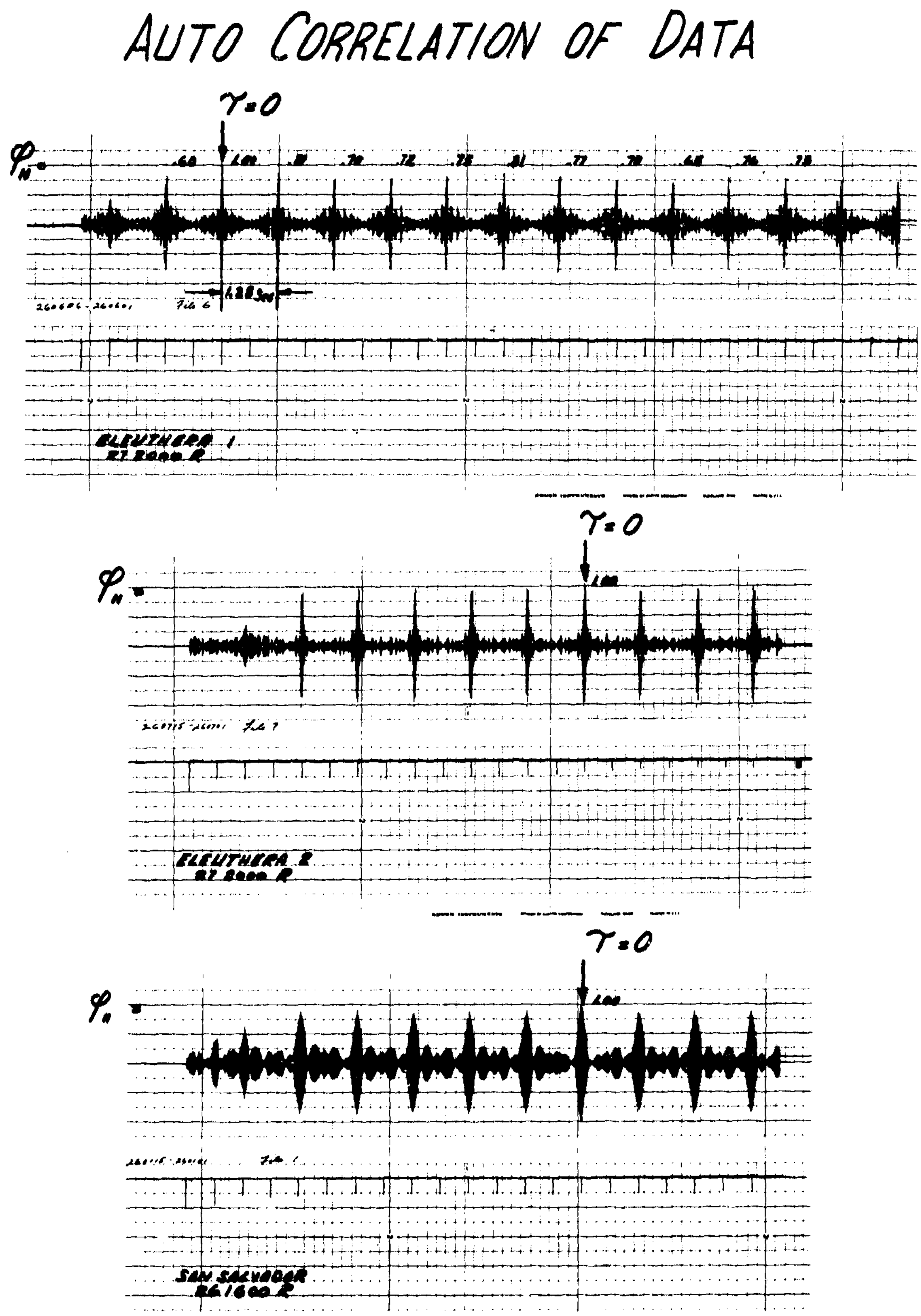


Fig. 7 - Resulting autocorrelation functions for individual data stations

# CROSS CORRELATION OF DATA PAIRS

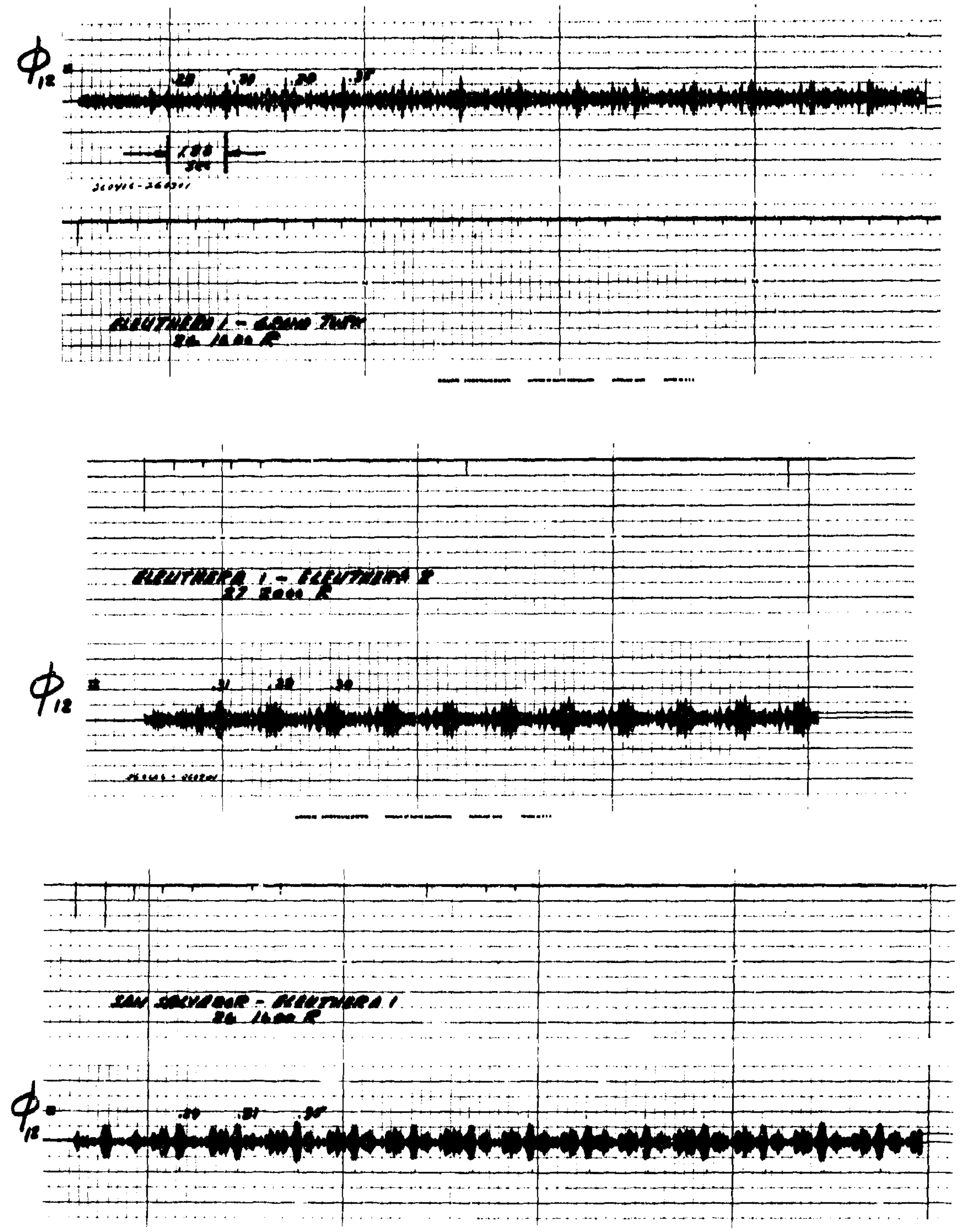


Fig. 8 - Resulting crosscorrelation functions for data station pairs

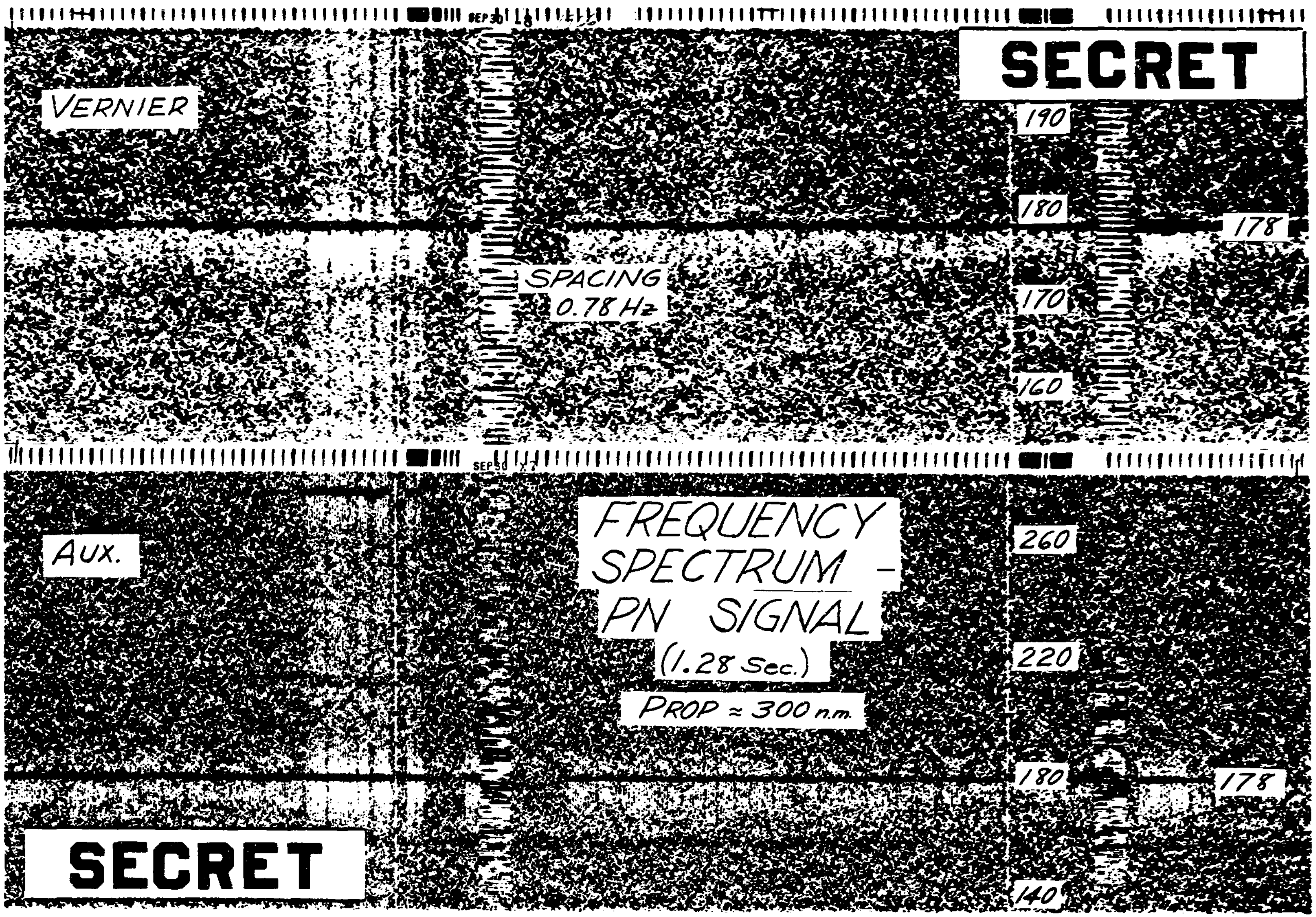


Fig. 9 - Lofargram of PN signals propagated about 300 N. M.

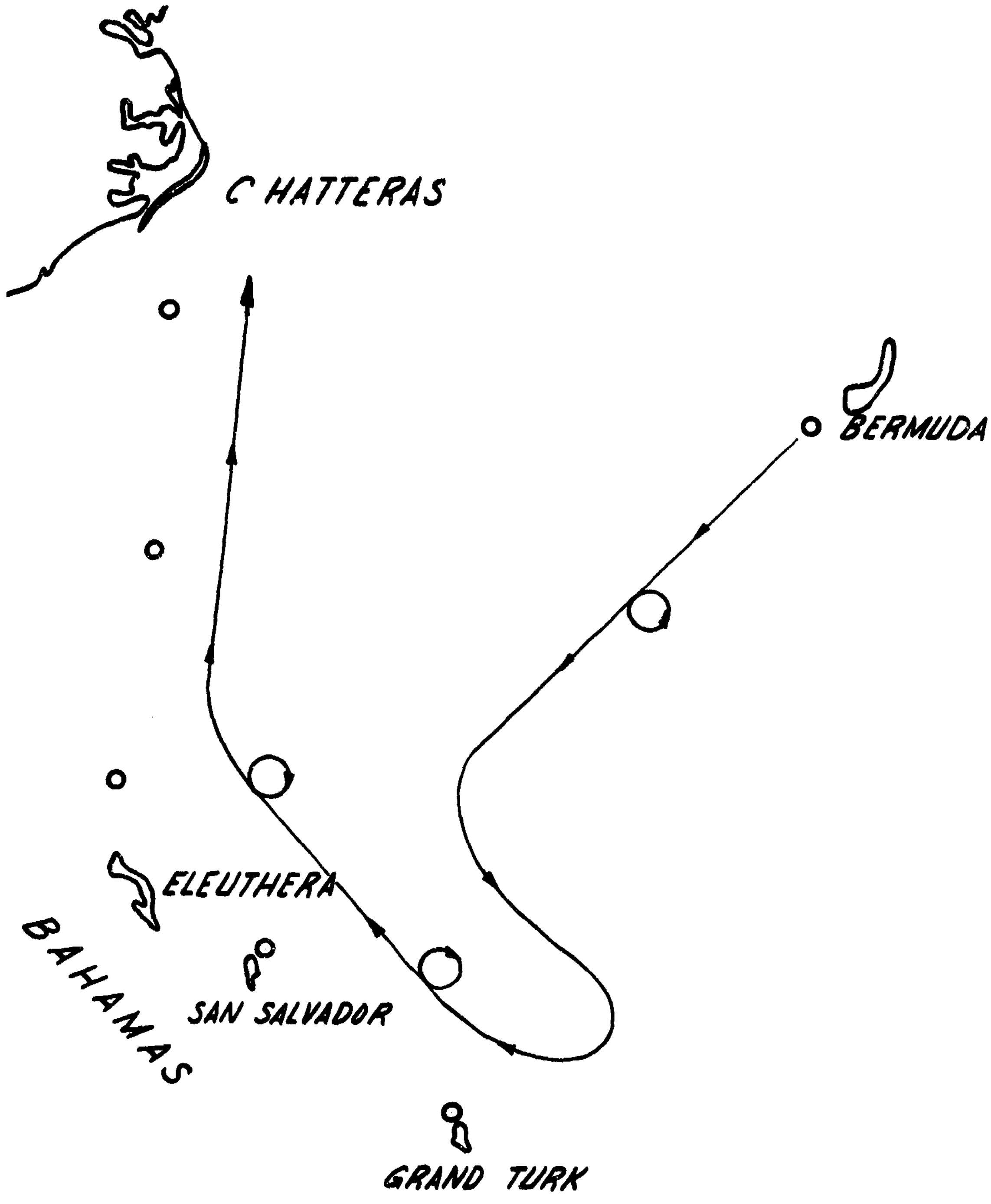


Fig. 10 - Proposed operation for August 1967

## APPENDIX A

Location of NRL Personnel, August, 1966 Field Experiment

Receiving Stations:

| | | |
|---|---|---|
| Eleuthera | : | H. L. Peterson |
| San Salvador | : | D. C. Coulter, G. G. Nacht |
| Grand Turk | : | NAVFAC Personnel |
| Cape Hatteras | : | NAVFAC Personnel |
| Bermuda | : | C. McCoy, J. M. Shaw |

Transmitting Station:

| | | |
|---|---|---|
| USS WITEK | : | Ray Smith, USNUSL |

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Various groups rendered cooperation and assistance to this research which was above and beyond their operational missions. It is hereby gratefully acknowledged as follows:

NAVELECSYSCOM, Washington, D. C.

COSYL, Norfolk, Virginia

NAVFAC stations accommodating NRL personnel and recording equipment, supplying signals and assistance as needed: Eleuthera, San Salvador.

NAVFAC stations recording signals using station personnel and recorders: Grand Turk, Cape Hatteras.

Thanks is also due to USNUSL personnel for the cooperation which made this exercise possible.

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LONG BASELINE CORRELATION EXPERIMENTS (Unclassified Title)

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

An interim report on a continuing problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

D. C. Coulter and H. L. Peterson

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13. ABSTRACT (Secret)

A preliminary experiment to measure the existence of signal coherency over very long baselines is described. Data for these measurements was obtained by NRL with the cooperation of USNUSL in allowing collaboration with their previously scheduled ARTEMIS propagation experiment. The data was recorded at SOSUS stations, mostly by NRL personnel for data processing at the Laboratory via digital computer. Initial results indicate the correlation coefficient of about 0.35 observed for one data run over a baseline distance of 450 nm. Additional field collection and laboratory analysis are planned to establish the range of possible values with greater accuracy and consistency. These studies are believed relevant to Navy needs, as follows:

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In addition to the above, there is some indication of possible jamming effects on SOSUS stations in the upper portion of the frequency range, by pseudo-random noise signals of sequence length utilized for this experiment.

Follow-on experiments to further illuminate the above problem areas are planned.



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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Underwater sound | | | | | | |
| Transmission | | | | | | |
| Propagation | | | | | | |
| Long range | | | | | | |
| Baselines | | | | | | |
| Signals | | | | | | |
| Recordings | | | | | | |
| Receiving stations | | | | | | |
| Correlation | | | | | | |

**UNITED STATES GOVERNMENT**

# Memorandum

7100-130

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**REPLY TO ATTN OF:** Burton G. Hurdle (Code 7103)

**SUBJECT:** REVIEW OF REF (A) FOR DECLASSIFICATION

**TO:** Code 1221.1

**REF:** (a) "LONG BASELINE CORRELATION EXPERIMENTS" (U) D.C. Coulter and H.L. Peterson, Sound Division, NRL Memo Report No. 1797, 25 July 1967, (S-NF)

1. Reference (a) describes experiments to determine the magnitude of signal coherence over very long base lines for use by the ARTEMIS System. Initial results indicated a correlation coefficient of about 0.35 over a base line of 450 nm.

2. The technology and equipment of reference (a) have long been superseded. The current value of these papers is historical.

3. Based on the above, it is recommended that reference (a) be declassified and released with no restrictions.

Burton G. Hurdle

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NRL Code 7103

CONCUR:

John S. Perkins 9/13/02

J.S. Perkins Date
Acting Superintendent, Acoustics Division

CONCUR:

Tina Smallwood 9/18/02

Tina Smallwood Date
NRL Code 1221.1

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